

*AMiBA 2001: High-z Clusters, Missing Baryons, and CMB Polarization*  
*ASP Conference Series, Vol. 999, 2002*  
*L-W Chen, C-P Ma, K-W Ng and U-L Pen, eds*

## Concluding Remarks: From Current CMBology to its Polarization and Sunyaev-Zeldovich Frontiers *circa TAW8*

J. Richard Bond

*Canadian Institute for Theoretical Astrophysics, University of Toronto,  
 Toronto, Ontario, M5S 3H8, Canada*

**Abstract.** I highlight the remarkable advances in the past few years in CMB research on total primary anisotropies, in determining the power spectrum, deriving cosmological parameters from it, and more generally lending credence to the basic inflation-based paradigm for cosmic structure formation, with a flat geometry, substantial dark matter and dark energy, baryonic density in good accord with that from nucleosynthesis, and a nearly scale invariant initial fluctuation spectrum. Some parameters are nearly degenerate with others and CMB polarization and many non-CMB probes are needed to determine them, even within the paradigm. Such probes and their tools were the theme of the TAW8 meeting: our grand future of CMB polarization, with AMiBA, ACBAR, B2K2, CBI, COMPASS, CUPMAP, DASI, MAP, MAXIPOL, PIQUE, Planck, POLAR, Polatron, QUEST, Sport/BaRSport, and of Sunyaev-Zeldovich experiments, also using an array of platforms and detectors, e.g., AMiBA, AMI (Ryle+), CBI, CARMA (OVROmm+BIMA), MINT, SZA, BOLOCAM+CSO, LMT, ACT. The SZ probe will be informed and augmented by new ambitious attacks on other cluster-system observables discussed at TAW8: X-ray, optical, weak lensing. Interpreting the mix is complicated by such issues as entropy injection, inhomogeneity, non-sphericity, non-equilibrium, and these effects must be sorted out for the cluster system to contribute to “high precision cosmology”, especially the quintessential physics of the dark energy that adds further mystery to a dark matter dominated Universe. We will have to address “Is it cluster evolution or is it cosmology?”. The answer will be both, but we can be optimistic that, with the huge data influx, computational power increase, and talented people joining the adventure, we can handle both observationally, theoretically and phenomenologically.

### 1. Concordance? and its Consequences

#### 1.1. The Beginning of the End or the End of the Beginning?

In April 2001, just predating TAW8<sup>1</sup>, the Boomerang and DASI teams independently unveiled remarkably similar power spectra of the *primary* anisotropies

---

<sup>1</sup>This paper blends an introductory primary CMB talk with my conference summary. Only a few CMB references are given, organized by date (April'99, April'00, April'01). The perpetrators

of the CMB, those which can be calculated using linear perturbation theory (Fig. 1). The analysis of cosmological parameters was in accord with indications from Large Scale Structure (LSS), Supernova (SN1), and a variety of other observations, pointing towards everyone's neo-standard model at this meeting,  $\Lambda$ CDM. Typical  $\Lambda$ CDM parameters are taken to be:  $\Omega_{tot} = 1$ ;  $\Omega_\Lambda \approx 0.7$ ; Hubble parameter  $h \approx 0.7$  from the Hubble key project;  $\Omega_m \sim 0.3$ , including  $\sim 0.04$  in baryons, the rest in cold dark matter;  $n_s = 1$  as the slope of the initial density power spectrum, the scale-invariant Harrison-Zeldovich-Peebles value; overall mass density power normalized to have  $\sigma_8 \sim 0.9$ , with  $\sigma_8$  the *rms* (linear) density fluctuation level on a cluster-scale ( $8 h^{-1}$  Mpc). The baryon density choice  $\Omega_b h^2 \approx 0.02$  is the Big Bang Nucleosynthesis result calibrated with the deuterium abundance estimated from absorption lines in QSO spectra.

From the early 80s onward, CMB observations were used with LSS information, as embodied in angular and redshift galaxy surveys, cluster and other rare event abundances, cluster clustering, and velocity flows to constrain the cosmological parameters defining the space. Even in the days of CMB upper limits predating the COBE/FIRS/SP91/Tenerife and subsequent detections, the CMB was a powerful constrainer. When the COBE detection was combined with LSS, a great collapse occurred in parameter space, which was further constricted by detections on intermediate angular scales throughout the 90s, and which Boomerang, DASI and Maxima have now turned into bulls-eye determinations on some key parameters (Fig. 2), focussing even more than in the April'00 release.

It appears from Fig. 1 that multiple peaks and dips in the CMB have been found – a dominant first peak, a less prominent second one, and a hint of a third one, with interleaving dips (April'01). These are even in roughly the right location of a long-standing prediction of adiabatic inflation-based models with little mean curvature. The physics of the  $C_\ell$  peak structure is based on acoustic oscillations and velocity flows as the photon-baryon fluid viscously passed from tight coupling to free-streaming at photon decoupling (redshift  $z_{dec} \sim 1100$ , about 0.4 Myr after the “Big Bang”), generating the “damping tail” evident in the “best-fit” theoretical model shown in Fig. 1.

The maps from which the  $C_\ell$  bandpowers are derived are largely noise-free images of soundwave patterns seen through the photon decoupling “surface” of width  $\sim 10 h^{-1}$  Mpc that defines the thick-to-thin transition. This is quite a bit smaller than the comoving “sound crossing distance” at decoupling,  $\sim 100 h^{-1}$  Mpc (i.e.,  $\sim 100$  kpc physical), below which density oscillations and velocity flows can be observed. After, photons freely-streamed along geodesics to us, mapping (through the angular diameter distance relation) the post-decoupling spatial structures in the temperature to the angular patterns we observe now. The free-streaming along our (linearly perturbed) past light cone leaves the pattern largely unaffected, except that temporal evolution in the gravitational potential wells as the photons propagate through them leaves a further  $\Delta T$  imprint, called the integrated Sachs-Wolfe effect.

---

of the advances mentioned in this summary, and associated references, can be found elsewhere in these proceedings.

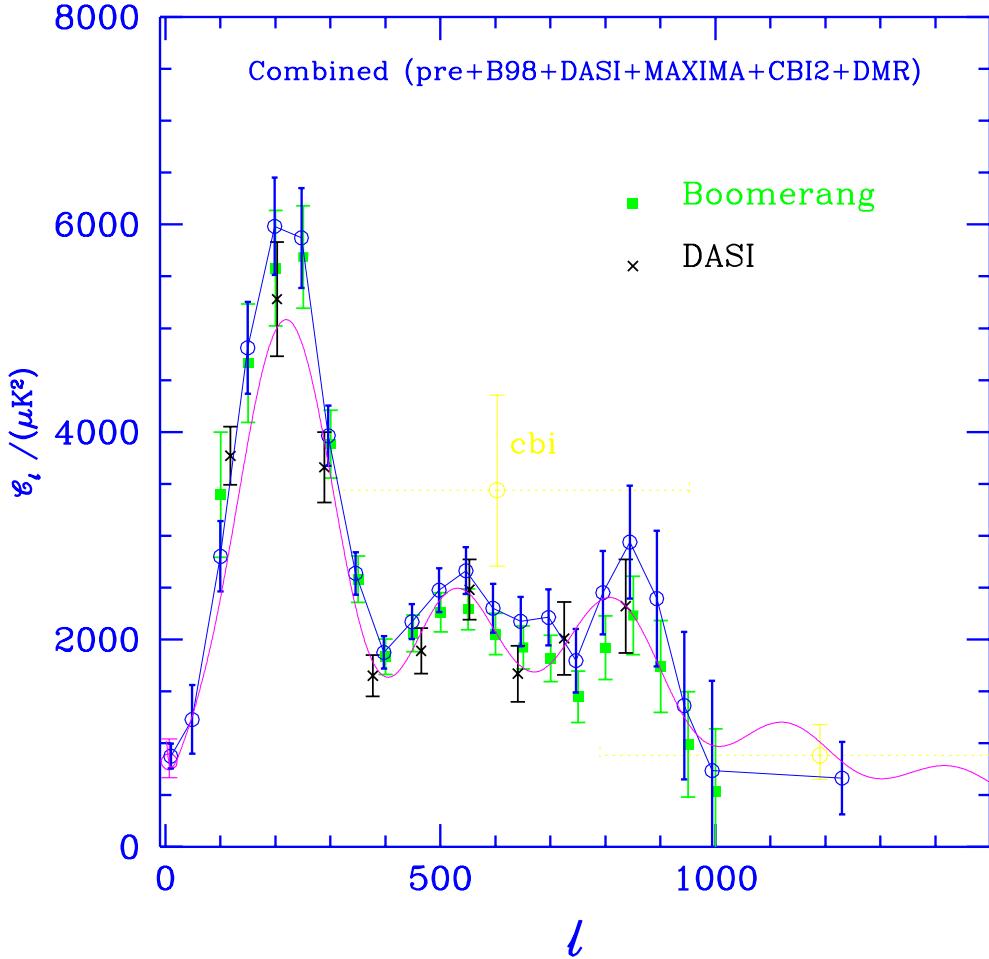


Figure 1. The optimally-combined power spectrum  $C_\ell$  grouped in bandpowers using all current data (circles, joined by a light line) is contrasted with that for Boomerang-LDB (squares), DASI (crosses) and DMR (point at low  $\ell$ ). “pre” denotes TOCO, Boom-97 and 19 other experiments predating April’99. This heterogeneous “prior CMB” mix is quite consistent with what Boomerang, DASI and Maxima show, with much larger errors. CBI2 denotes the two published CBI points, only a small fraction of the total CBI data. A Boomerang best-fit model using the weakH+LSS+flatU prior is also shown. In spite of the 10% calibration and 13% beam uncertainties for Boomerang, little adjustment of its median values was required by the other data. A caveat: DASI’s fields overlap about 5% of the Boomerang area, so there is correlation between Boomerang and DASI. This is not taken into account here, but the consistency in the overlap regions are currently being explored. The optimal  $C_\ell$  without DASI included looks similar to the one shown, as might be expected given the consistency of the two power spectra (and also the similarity in derived cosmic parameters).

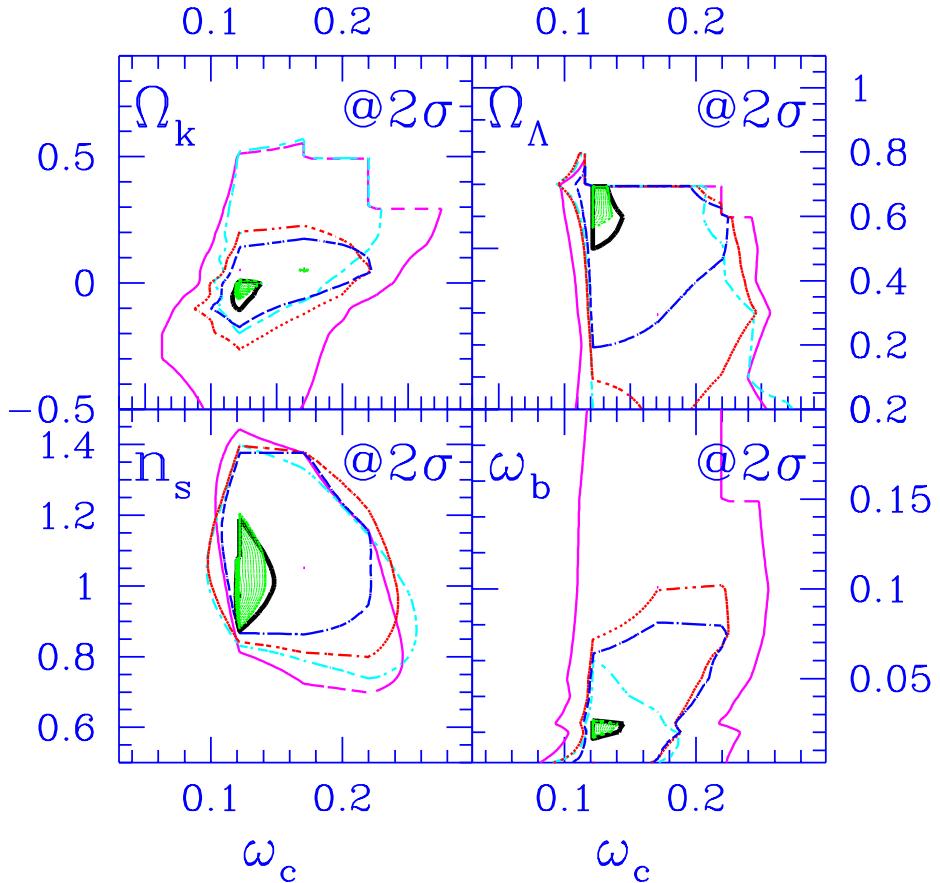


Figure 2.  $2\sigma$  likelihood contours for the dark matter density  $\omega_c = \Omega_{cdm}h^2$  and  $\{\Omega_k, \Omega_\Lambda, n_s, \omega_b\}$  for the LSS+weakH prior, and the following CMB experimental combinations: DMR (short-dash); the “April’99”+DMR data (short-dash long-dash); TOCO +(April’99+DMR) data (dot short-dash); “prior-CMB” = Boom-97 +(TOCO+April’99+DMR) data (dot long-dash); Boomerang + DASI + Maxima-1 + “prior-CMB” data (heavy solid, all-CMB). These  $2\sigma$  lines tend to go from outside to inside as more CMB experiments are added. The smallest  $2\sigma$  region (dotted and interior) shows SN1+LSS+weakH+all-CMB, when SNI data is added. For the  $\Omega_\Lambda$ ,  $n_s$  and  $\omega_b$  plots, the flatU prior,  $\Omega_{tot}=1$ , has also been assumed, but the values do not change that much if  $\Omega_{tot}$  floats. The main movement from Apr’00 to Apr’01 was that  $\omega_c$  localized more around 0.13 in all panels, and the  $\omega_b$  contour in the lower right panel migrated downward a bit to be in its current good agreement with Big Bang Nucleosynthesis.

Of course there are a number of other signals that are also present in the maps, so how can we be confident that Fig. 1 really offers a glimpse of fluctuation power at  $z_{dec}$ ? Known contaminating signals include the Galactic foregrounds of bremsstrahlung, synchrotron and dust emission, extragalactic radio and infrared sources. As well, *secondary* anisotropies associated with post-decoupling non-linear effects are also present. These include weak-lensing by intervening mass, Thompson-scattering by the nonlinear flowing gas once it became "reionized" at  $z \sim 10 - 20$ , the thermal and kinematic SZ effects, and the red-shifted emission from dusty galaxies. All secondary and foreground sources leave non-Gaussian imprints on the CMB sky, and all but the kinematic SZ effect have different spectral signatures to aid in signal separation. For some experiments (DASI, CBI), it has been crucial to remove sources, for others like Boomerang, relatively contamination-free channels and regions can be found. We have been lucky that many of these signals are subdominant at the angular scales we are probing in Fig. 1. As precision improves, signal separation will loom large.

Because of the CMB+LSS success, we did not see at TAW8 as many of the usual comparison cosmologies as we used to at such meetings, the open  $\Lambda$ CDM, the hot/cold hybrid  $H\Lambda$ CDM,  $\tau$ CDM, the tilted  $t$ CDM, the cluster-normalized old-standard  $s$ CDM. Nor were cosmic defect models in evidence. Though many of the  $x$ CDM's may have fallen away, we now see  $Q$ CDM appearing on the stage, with  $Q$  an ultra-low mass scalar field, often called quintessence, that dominates at late times. Thus  $\Omega_Q$  replaces  $\Omega_\Lambda$ , and an effective  $Q$ -dynamics is cast (though none too well) in terms of a mean pressure-to-density ratio  $w_Q = \bar{p}_Q/\bar{\rho}_Q$ , an effective equation of state (EOS). Well not so effective, since  $Q$  is a spatially-dependent field, or may be. In spite of a huge number of quintessential papers,  $Q$  would better stand for question mark. For  $\Lambda$ ,  $w_Q = -1$ , but  $w_Q < -1/3$  would get our patch of the Universe into acceleration, apparently with no new comoving space to be revealed.

If there really is a  $\Lambda$ CDM/ $Q$ CDM concordance, then apart from the wide grins of the "often in error, never in doubt" cosmologists, hubrous abounding, we may also hear theorists' lament: Where are the anomalies for wild and fun theorizing? Between our state now, with its large-ish error bars and the never-ending worry about the systematic rather than the statistical, and with the exquisite data from a vast array of experiments coming down the pipe, there is still much room for a cosmic surprise. Perhaps the greatest of all will be if the models of the 80's do in fact describe how all of the structure formed in the Universe, albeit with a mysterious dark energy accelerating us. Even if  $\Lambda$ CDM, theorists are still at play, though not so much at TAW8 which was concretely directed to the empirical. Just look to the dark energy, the struggles to tie the latest inflation our observable patch of the Universe now seems to be caught in with the early inflation needed to "smooth the universe" and solve causality problems, and, incidentally, to generate quantum noise from which all observed cosmic structure originated. Look to the dialogues between those of the M-theory brane worlds and the physical cosmologists, reigniting the early universe connection that we were in danger of losing – what with the (clustering) dark matter being supposed cold for so long and with inflation being generic but tunable to meet all demands (though not without highly baroque additions).

### 1.2. Broad Truths from the CMB+LSS

Most amazing about Fig. 1, COBE’s FIRAS experiment, the accumulating LSS information, now coming in a torrent with 2dF, Sloan and higher redshift surveys, etc., is that the paradigm appears to hold: a hot Big Bang, with an almost perfect  $T_{\gamma*} = 2.725 \pm 0.001\text{K}$  blackbody spectrum that must have come to us from beyond the most distance SZ cluster,  $z \gtrsim 1$ . That  $\mathcal{C}_\ell$  is significantly positive at  $\ell \sim 1000$  argues against a large  $\exp[-2\tau_C]$  damping multiplier, where  $\tau_C \sim 0.1(\omega_b/0.02)(\omega_m/0.15)^{-1/2}((1+z_{reh})/15)^{3/2}$  is the Thompson optical depth to the epoch  $z_{reh}$  of reheating. Thus, though much pregalactic energy injection at  $z \sim 200$  is still possible, it does not look like it. The FIRAS limit of  $4\bar{y} < 10^{-4}$  on fractional energy input into the CMB from the lack of a Compton cooling spectral  $y$ -distortion further implies no large entropy injection could have occurred at lower  $z$  into the gas, strongly limiting the role explosions can have had in LSS development. The beautiful direct connection of the small  $\Delta T$  fluctuations to the density amplitudes now – on the same spatial scales – strongly support the gravitational instability picture of structure formation. That it forms hierarchically, from small to big, is of course obvious from LSS observations at various redshifts, but  $n_s \sim 1$  from the CMB adds further positive support.

The primary CMB fluctuations are quite Gaussian, according to COBE, Maxima, and now Boomerang analyses. A non-Gaussian component, possibly subdominant, of the primordial fluctuations can still work, but it is encouraging for inflationists where Gaussian statistics are the natural (but not only) outcome. Cosmic defect and cosmic string models of structure formation are more challenged by the peaks and dips of  $\mathcal{C}_\ell$ , which are very difficult to get, than by the Gaussianity.

We know the gravitational instability of a hierarchical Gaussian random density field leads naturally to the cosmic web interconnections and the prevalence of superclustering that we seem to find observationally at low and high redshifts — a framework for thinking about the cluster/group system that was a main theme of TAW8. The web consists of massive clusters with overdensities  $\delta \gtrsim 100$ , filaments with  $\delta \sim 5 - 10$ , which bridge massive clusters, groups which bead the bridges, membranes with  $\delta \sim 2$  which join the filaments, and the voids with  $\delta < 0$  dominating the space but not the mass. This picture is of course borne out by all the large simulations reported at TAW8, sizes ranging from  $128^3$  for a “Schrodinger equation” cosmological calculation to  $256^3$  and even  $512^3$  for hydro and  $N$ -body, and to  $1000^3$  for  $N$ -body. Just a decade ago, a  $128^3$   $N$ -body was a tour de force. We also heard much about semi-analytic methods in many different guises that fit into this web picture, the halo model and the peak-patch model with clustering included in both, and of course many variants of Press-Schechter-ism.

## 2. Using the Cluster/Group System and LSS to Probe a $\Lambda$ U

Determining the dark energy EOS is the new mantra for the empirical component of our subject, and because it turns out that CMB cannot determine it by itself (unavoidable near-degeneracies exist among cosmological parameters,  $w_Q$  in particular), it will keep all cosmic probers in business, probably for a very

long time, all in the cause of “breaking degeneracies”, an oft-repeated phrase at TAW8. No longer will the target be whether it is curvature energy  $\Omega_k = 1 - \Omega_{tot}$  or  $\Omega_\Lambda$  that makes up the deficit between  $\Omega_m$  and unity, rather it is the much subtler and harder EOS (and more refined) dynamics that we must use our probes to determine. High redshift supernovae, to be sure, will be used in large surveys, but also: weak lensing of large scale structure and cluster abundances as a function of redshift, informed by Sunyaev-Zeldovich, optical, X-ray and lensing surveys, possibly group and galaxy evolution, i.e., the themes and ambitious plans expressed at TAW8. And though we know the sad history of how the classic grand cosmological tests of the deceleration parameter ran afoul of whether it is the “messy astrophysics of complex evolving objects” or “cosmology”, we have little choice but to understand our systems well enough so they too can become parameter-estimation tools. How else but through astronomy can we learn about perhaps the greatest mystery in all of physics?

**Clusters are Not Simple:** When the differences we were going for were vast (cluster abundances as a function of redshift for  $\tau$ CDM or sCDM *cf.*  $\Lambda$ CDM, given normalization to clusters now), one could be slightly cavalier about the complexity of clusters – the deepest potential wells in the known universe, nice equilibrium systems. That is, theoretical naivete could be forgiven. Even the use of the Press-Schechter mass functions,  $\beta$ -models, isothermality, spherical profiles, single-phase assumptions, ignoring the known complications of magnetic fields, cooling flows, metal/energy injections, and the emerging complications revealed by the new Chandra and XMM data, could be forgiven as long as great accuracy was not claimed.

I believe success in the dark energy EOS enterprise using clusters is possible, for many reasons in evidence at TAW8: the X/optical/lensing/SZ cluster information here now and planned; the overwhelming avalanche of high quality survey data to come, terapixels-worth; the ambitious theoretical work using hydrodynamics, N-body, analytic and semi-analytic tools being undertaken to understand the data and also forecast and prepare for future experiments; the computing horsepower that promises Monte Carlo simulation to take theory fully forward into the observational space – with theorists becoming fully integrating into the experimental/observational teams; and especially with the energetic young researchers avidly embracing the complexity.

On the other hand, clusters in the X-ray at higher resolution do not look simple, red galaxy numbers per cluster mass must fluctuate, merging at  $z \sim 1$  will be ubiquitous, so equilibrium may not prevail, especially in the most interesting objects that catch our various “eyes”.

**Some Clusters May Not Be Too Complex:** Armed with all of the probes and surveys at our disposal, we should be able to select physically-understood cluster subsamples for which we can be reasonably sure that the cosmic parameters we deliver will be with calculable systematic errors and no bias in value, not just with the small statistical errors that naive theory forecasts. Of course this is preaching to the converted. Given the range of talks at TAW8, almost all terrain we need to cover was covered at some level:

- Metals in the intracluster/intragroup medium, and in the higher  $z$  intergalactic medium ( $\lesssim 20\%$  apparently affected at  $z \sim 3$ ), relating to, but far from solving, the major issue of energy injection into these media.
- Filaments may be more SZ-observable if the energy injection is strong. Related questions of the effects feedback has on group and cluster gas probes as a function of redshift remain unanswered.
- Great plans for SZ-interferometer surveys: AMiBA is developing MMIC HEMTs at 90 Ghz, novel correlators, platform, etc. with survey plans to probe deep, medium and shallow, with coverage 3, 70 and 175 sq deg. The CARMA integration of the BIMA and the OVRO mm arrays, both of which have had a spectacular history already in SZ science, the CBI, targeting  $z < 0.1$  clusters, the SZA at 30 GHz, AMI at 15 GHz and MINT at 140 GHz will all considerably enhance the SZ effort.
- Great plans for bolometer-based surveys: the CSO with BOLOCAM on Mauna Kea soon to observe, ACBAR at the South Pole already observing, SuZIE of course, the LMT (large mm telescope) in Mexico, eventually Planck. There is much excitement about bolometer arrays on ground-based  $\sim 6m$  telescopes, e.g., the ACT proposal for 3 32x32 pixel bolometer arrays delivering 1.7' resolution.
- Progress in analysis pipelines for of all of the different types of data that is coming, though much remains to do. For SZ, component signal separation and source identifications are crucial. It is ironic that the primary CMB, so long our target, is a nuisance confusion to be filtered out. For optical spectra, Principal Component Analysis was effectively used. Only 3 eigenmodes describing old, field and post-Star-Formation spectra were needed, and helped clarify cluster gradients and the Butcher/Oemler effect.
- The intense work in the optical on clusters and groups, both for specific objects and in heroic surveys. The now venerable CNOC1,2. The 100 sq deg “Red Sequence Cluster Survey”, with its 22 patches of 5 sq deg, can deliver optically-identified clusters in abundance: 200 at  $z > 1$ , 500 at  $z > 0.7$ , 2700 at  $z > 0.4$ . More ambitious areas are planned: RCS2’s 1000 sq deg; VISTA’s 10000 sq deg; Megacam on CFHT 9 sq deg/night, applied to the CFH Legacy Survey. By contrast, SDSS though wide is relatively shallow, with the clusters dying off above  $z \sim 0.5$ . The 130 sq deg Las Campanas survey used a 1 m telescope to get clusters in the  $0.35 < z < 0.9$ , with extensive follow-up, with application to the key LSS cluster clustering  $r_0 - d_c$  figure.
- Groups of  $\sim 10^{13-14} M_\odot$  and poor clusters are such a mix, making detection ambiguous, prone to superposition. Still, they are the *rms* objects in the universe, so we must understand them, and there is some progress there on selected populations.
- The new substantive X-ray luminosity functions at different redshifts, BCS, ROSSI, REPLEX, EMSS, SHARC, NEP, MACS – do I have them all? – giving a consistent picture it seems. Would that the relation of  $L_X$

to mass was simple,  $n(T_X)$  much preferred, of course, but the clusters that can be used are still small in number. Still, the  $\Lambda$ CDM concordance model seems to work yet again.

- The X-ray studies of individual clusters revealing finer detail (subarcsec resolution for Chandra) and complexity in the intracluster medium (temperature inhomogeneity, “cold fronts” et al., and, as in all such meetings, cooling flows). Can we cosmic hydro simulators handle this richness of detail?
- The beautiful lensing mass maps of individual clusters, and a supercluster example, and the amazing strongly-lensed clusters with powerful and multiple arcs at high  $z$ ; and galaxy-galaxy lensing too.
- The weak-lensing probe of LSS a tool to get beyond galaxy biasing to the mass density power spectrum, and through that and higher order non-Gaussian statistics, to cosmic parameters, including  $w_Q$ .
- The heavy use of new instruments (Subaru figured prominently here, as of course did Chandra and XMM), the use of venerable telescopes, sometimes newly instrumented (optical surveys at CFHT, CTIO, etc.), and an imaginative panoramic optical imager, an array of small telescopes for weak lensing and other mappings.

### 3. The Primary CMB Snapshot and the Race to Polarization

#### 3.1. The Recent Primary CMB Experiments

Fig. 1 gives the current snapshot of our knowledge of the power spectrum  $\mathcal{C}_\ell \equiv \ell(\ell+1)\langle|\Delta T|_{\ell m}^2\rangle/(2\pi)$  as a function of multipole  $\ell$  in a spherical harmonic expansion  $(\Delta T)_{\ell m}$  of *primary* total temperature anisotropies. All published CMB experimental results as of Fall 2001, including their quoted calibration and beam errors, are compressed into 22 bandpowers:

- BOOMERanG-98, a long duration balloon (LDB) experiment took a 1.2m telescope aloft from McMurdo Bay in Antarctica in late Dec 1998 with 16 bolometers cooled to 300 mK at frequencies 90, 150, 220 and the dust-dominated 400 GHz. It circled the Pole for 10.6 days, mapping 1800 sq degs with a best resolution of 10.7' (Gaussian  $\ell_s \approx 750$ ). For April'01 (the results shown here), 800 sq deg and four of five 150 GHz bolometers were used, about eight times more data than was used for April'00. We are now analyzing  $\sim 1300$  sq degs with 3.5' pixels. A 10% calibration and a 13% beam uncertainty must be included.
- MAXIMA-I, a short duration (overnight) balloon, used bolometers cooled to 100 mK to map 124 sq deg to  $\sim 10'$ . There was a 4% calibration and a 5% beam uncertainty.
- DASI, the South-Pole-based 13 element (0.2m antennae) Degree Angular Scale Interferometer with 30 GHz HEMTs, mapped 288 sq deg in 32 fields

of 3.4 deg diameter over the  $\ell$ -range 100-900. There was a 4% calibration uncertainty, but none in the beam.

- CBI, the Chile-based 13 element (0.9m dish) Cosmic Background Imager interferometer with 30 GHz HEMTs, has mapped three 10 sq deg mosaic regions and three 0.44 sq deg deep fields in 2000-01, probing from  $\ell \sim 300$  up to  $\sim 4000$ , i.e., well beyond the Boomerang range into the “damping tail”. There was a 3% calibration uncertainty, but again none in the beam. CBI2 denotes the Nov’00 CBI bandpowers that used two of the deep fields and only 5% of the total data in the analysis. The CBI team is collaborating with our group at CITA in a much more extensive analysis of the year-2000 CBI mosaic and deep field data, which will significantly sharpen the focus in the  $\ell \gtrsim 1000$  regime ( $\sim$  Jan’02 release).
- Boom-97, the North American test flight.
- TOCO, a Chile-based telescope which used SIS as well as HEMT receivers.
- COBE-DMR, with resolution  $\ell_s \approx 17$ .
- April’99: 19 other earlier CMB experiments” that had bandpowers (or upper limits) we were using by April 99. “prior CMB” or “pre” adds TOCO and Boom-97 to the mix, i.e., all CMB data before the April’00 Boomerang release.

The band positions and  $\Delta\ell=50$  widths were chosen to be those of the April’01 Boomerang release (Netterfield et al., 2001), except a narrower first bin ( $3 \leq \ell \leq 25$ ) was added to encompass the COBE DMR results and the  $\ell > 1025$  region beyond the Boomerang range, but encompassing CBI2, is much wider ( $\Delta\ell=500$ ).

### 3.2. More on the Cast of Cosmic Parameters

It has long been recognized that the measurement of the predicted  $\mathcal{C}_\ell$  structures such as peaks and dips and damping tails could determine cosmic parameters. The “minimal” set  $\{\Omega_{tot}, \Omega_b h^2, \Omega_{cdm} h^2, \Omega_{hdm} h^2, \Omega_{wdm} h^2, n_s, \sigma_8, \tau_C\}$  defined an operative parameter space including hot, warm or cold dark matter, as well as baryonic, from 1982 onwards. (We now prefer to use  $\omega_j \equiv \Omega_j h^2$  because it is related to the physical density rather than a ratio to the critical density.) A target (scalar) spectral index  $n_s$  was the Harrison-Zeldovich-Peebles 1, but even in 1982, nearly scale invariant emerged, with the tilt  $n_s - 1$  near to unity. Cosmologists treated it as a free parameter. We parameterized the power amplitude in initial mass density fluctuations by a “galaxy biasing factor” that was almost exactly  $\sigma_8^{-1}$ ;  $\sigma_8$  became the more widely adopted normalizer in 1985. Whether there was early reheating, embodied in  $\tau_C$ , has always been a question.

The ancient  $\Omega_\Lambda$ , never as abhorrent to cosmologists as it was to particle physicists, was resurrected in the mid-80s under the “what you see is what you get” mantra that Jim Peebles chanted for us based on the annoying ubiquity of  $\Omega_m < 1$ . For me it came into sharp focus in 1986, since  $\Omega_\Lambda$  was one of the ways within the inflation paradigm to help explain the large scale power first seen in cluster clustering, then in velocity flows, then in galaxy clustering. In response,

we were actively considering  $x$ CDM models that were: open (oCDM); hot/cold hybrids; high in  $\Omega_b/\Omega_m$  (BCDM); radically “broken scale invariance” cases, with hills and/or valleys in  $n_s(k)$ ; tilted ( $n_s \sim 0.6$ ); high in the density of relativistic decay products of decaying keV-level neutrinos ( $\tau$ CDM); isocurvature, from quantum noise in scalar fields other than the inflaton; adiabatic/isocurvature hybrids. Even the venerable isocurvature baryon-dominated model of the 70s, with  $\Omega_{tot} < 1$  and  $n_s$  far from scale invariance, was resurrected, again by Peebles.

In the mid-80s, it was also recognized that tensor modes in the temperature fluctuations driven by gravitational wave zero-point fluctuations are a natural consequence of inflation, expanding the parameter space to include a relative tensor-to-scalar power  $\tilde{r}_{ts}$ , and a tilt  $n_t$  independent of  $n_s$ .

In the late-90s, in response to the  $\Lambda$  mystery, the EOS parameter  $w_Q$  was added, and sometimes so was  $\dot{w}_Q$ , a measure of its time variation.

### 3.3. Zeroing in on the Cosmological Parameters

Fig. 2 shows what happens to  $\Omega_{tot}$ ,  $\Omega_\Lambda$ ,  $\Omega_b h^2$ ,  $\Omega_{cdm} h^2$  and  $n_s$  in the parameter space described below as results from the Sec. 3.1. CMB experiments are added to LSS information on  $\sigma_8$  (as estimated from cluster abundances) and a density power spectrum shape/tilt parameter  $[\Gamma + (n_s - 1)/2]$ , with  $\Gamma \propto \Omega_m h$  (as estimated from large galaxy clustering surveys). The distributions in both these LSS parameters were taken to be quite broad, reflecting our desire to be uncontroversial among LSS practitioners. To this “LSS prior” probability, a “weakH prior” was imposed, requiring that the Hubble parameter and age of the universe satisfy  $0.45 < h < 0.9$  and  $t_0 > 10$  Gyr. Given the emerging CMB localization of  $\Omega_{tot}$  near unity, and the “inflationist’s theoretical prior” of penalizing the baroqueness which large mean curvature models with non-negligible  $|1 - \Omega_{tot}|$  suffer from, a “flatU prior” is adopted in 3 of the 4 panels (although it only makes a notable difference in the  $\Omega_\Lambda$  panel). The innermost (filled)  $2\sigma$  contour of Fig. 2 adds a “SN1a prior” to weakH+LSS, using the likelihood function in  $\Omega_\Lambda$ - $\Omega_m$  space derived from the high redshift Supernova 1a data.

With just the COBE-DMR+LSS data, the  $2\sigma$  contours already localize in  $\Omega_{cdm} h^2$  thanks to LSS. Fig. 2 shows there is also some localization of  $n_s$  around unity, and this is true even without the LSS prior. Although the April’99 data collectively shows evidence for a peak, it is not well enough localized for a useful curvature constraint. The picture begins to improve later in 1999, with  $\Omega_k$  localizing near zero when TOCO is added to the April’99 data. In April’00, results from the first CMB LDB flight, Boomerang, were announced, followed by those from Maxima, then the first CBI results in Nov’00. In April’01, Boomerang and DASI announced compatible power spectra, and Maxima improved its power spectrum with finer pixelization. Fig. 2 looks nearly identical if only Boomerang+DMR are used for the CMB experiments, and DASI+DMR also looks very similar, except  $\Omega_{cdm} h^2$  is not quite as localized.  $\omega_b$ ,  $\omega_c$  and  $\Omega_\Lambda$  really focus in with Boomerang.

The data therefore favour the simplest (least baroque) inflation theories: nearly flat, nearly scale invariant primordial fluctuations nothing on gravitational waves yet. The baryon density is nearly the Big Bang Nucleosynthesis value. CMB+LSS implies there is substantial dark matter and dark energy. As well, there are derived quantities we can get: Hubble constant ( $56 \pm 9$ ) and age

( $15 \pm 2$  Gyr) are consistent ( $62 \pm 6$ ,  $14 \pm 1$  if  $\Omega_{tot} = 1$ ). It is interesting to note that LSS data and CMB data are independently pointing to some of the same values. For example, the 2dF survey finds  $\Omega_{mh} = 0.20 \pm .03$ ,  $\Omega_b/\Omega_m = 0.15 \pm .07$  *cf.* our  $0.21 \pm .05$ ,  $0.14 \pm .03$ . If a light massive neutrino is added (HACDM models), CMB does not discriminate, and CMB+LSS just shifts things to slightly lower but still nonzero  $\Omega_\Lambda$ . However, to actually find evidence for or against at this stage, one needs LSS+CMB+SN1 to discriminate.

For the Quintessence EOS, we have found  $w_Q < -0.3$  at  $2\sigma$  for the CMB with the LSS+flatU+weakH priors. It is only when the SN1 prior is included that the  $w_Q$  constraint,  $< -0.7$ , becomes rather restrictive.

We are only at the beginning of the high precision CMB era. The bolometer-based ACBAR and the Arkeops and Tophat LDBs already have data, as does the HEMT-based interferometer VSA (Very Small Array) in Tenerife. CBI and DASI continue to accumulate data. And NASA launched the all-sky HEMT-based MAP satellite on June 30, 2001, with  $12'$  resolution. It is now mapping the sky at L2, the second Lagrangian point of the earth moon system some 1.5 million km away. Further downstream, in 2007, ESA will launch the bolometer+HEMT-based Planck satellite, with  $5'$  resolution.

How many independent cosmic parameter combinations can be measured with the CMB now? Four linear combos were forecasted to be determined to  $\pm 0.1$  for Boomerang, and this is the result obtained in the analysis of the real data. Adding the LSS-prior brought a 5th into this precision level. Our future involves the precision that all-sky mapping can give: for prior-less CMB-only,  $6/9$  to  $\pm .1$ ,  $3/9$  to  $\pm .01$  for MAP,  $7/9$  to  $\pm .1$ ,  $5/9$  to  $\pm .01$  for Planck. ( $\Omega_{hdm} h^2$  and  $\tilde{r}_{ts}$  are now added to our basic mix of 7).

### 3.4. Running or Planned Polarization Experiments

Given the total  $C_\ell$  of Fig. 1, we can forecast what the polarization signal and its cross-correlation with the total anisotropy will be, and which  $\ell$  range gives the maximum signal:  $\sim 5\mu\text{K}$  over  $\ell \sim 400 - 1600$  is a target for the  $E$ -mode that scalar fluctuations give. We cannot yet forecast the strength of the  $B$ -mode signal induced by gravity waves, since there is as yet no evidence for or against them in the data. However, the amplitude would be very small indeed even at  $\ell \sim 100$  where it is biggest: for now, detection is what theorists' dream of, because it would tell us so much about inflation, but we have great faith in the ingenuity of the experimentalists.

A great race is on to first detect the  $E$ -mode: bets on which team? The experiments discussed at TAW8, and listed in the abstract, range from many degrees to subarcminute scales. The PIQUE 95% CL upper limit of  $14 \mu\text{K}$  at  $\ell \sim 210$  and the similar ATCA limit (but at  $\ell \sim 4500$ ) are still well above the forecast, but we are getting there.

The target  $\ell$  range and amplitude of the forecasts has, of course, not escaped the notice of experimental designers; e.g., AMiBA, CBI with HEMTs, ACBAR, Boomerang-2K2, and eventually QUEST and Planck, of course, with polarization-sensitive bolometers, can all probe this range. Not surprisingly, the forecasts show a solid detection is likely for many of the proposed experiments, often with enough well-determined broad-band powers to use the results

for cosmology. Since polarization is such a necessary outcome of the adiabatic paradigm, the implications will be enormous (and exciting) if it fails to be there.

What about the competition from foreground and secondary polarization? For the SZ secondary, the contribution is small, but for Galactic foregrounds it could be large – not enough is known about them at the CMB observing frequencies. If we can unravel the signals that make it up the detections, the primary polarization will come into its own to augment total anisotropy in cosmic parameter estimation. It can break parameter degeneracies, e.g., those associated with allowing  $n_s(k)$  structure, by using the shift in the polarization  $\mathcal{C}_\ell$  peaks and dips relative to those for the total anisotropy.

The quest for the polarization signal is sufficiently exciting that the adventure travel offered, to the Atacama desert where the CBI is (and ALMA will be), to the South Pole for a winter-over, to Hawaii or California, is a bonus.

**Acknowledgments.** I would like to thank my fellow CITizen CMBologists and other Boomerang and CBI team members for an amazing trek over the past few years as the ups and downs of  $\mathcal{C}_\ell$  have been progressively revealed.

*Thanks from all of us to Lin-Wen, Jackie, Jean et al., for a great job of organizing us and to Fred and Pauchy for bringing us here. The hospitality, the city/mountain split venue, the cuisine, and the science, were all tremendous. Congratulations on the wonderful growth of effort in Taiwan associated with CosPA. We look forward to AMiBA science, and the many opportunities for the further meetings it will precipitate in our fast advancing subject.*

## References

- prior-CMB: Miller, A.D. et al., 1999, ApJ Lett 524, L1 [TOCO]; Mauskopf, P. et al., 2000, ApJ Lett 536, L59 [Boom-97]; Bond, J.R., Jaffe, A.H., & Knox, L. 2000, ApJ, 533, 19 [April'99 refs.]
- April'00: de Bernardis, P. et al., 2000, Nature 404, 995 [Boom'00]; Lange, A. et al., 2001, PRD, 63, 042001 [LSS-prior]; Hanany, S. et al., 2000, ApJ Lett 545, 5 [Maxima'00]; Jaffe, A. et al., 2001, PRL 86, 3475, astro-ph/0007333; Bond, J.R. et al., 2000, Proc. Neutrino 2000, astro-ph/0011377 [ $\Omega_{hdm}/\Omega_m$ ], Proc. CAPP 2000, astro-ph/0011379 [ $\Omega_Q-w_Q$ ]
- Nov'00: Padin, S. et al., 2001, ApJ Lett 549, 1 [CBI2]
- April'01: Netterfield, B. et al., 2001, ApJ, in press, astro-ph/0104460 [Boom'01]; de Bernardis, P. et al., 2001, ApJ, in press, astro-ph/0105296 [Boom-pks]; {Leitch, E.M. et al., Halverson, N.W. et al., Pryke, C. et al., } 2001, astro-ph/{ 0104488, 0104489, 0104490} [DASI]; {Lee, A.T. et al., Stompor, R. et al., } 2001, astro-ph/{0104459, 0105062} [Maxima'01]